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THE BOUNDARY OF THE GEOMAGNETIC FIELD

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Space experiments have now definitely established that the distant geomagnetic field terminates abruptly rather than simply merging into the interplanetary field. The region occupied by the geomagnetic field is termed the "magnetosphere" because the motion and many other properties of the terrestrial plasma and energetic particles contained therein are controlled to a large extent by the geomagnetic field. The outer boundary of the magnetosphere is called the "magnetopause" in analogy to terminology prevalent in the description of the lower portions of the atmosphere. The interplanetary plasma beyond the magnetopause is observed to flow ever outward from the sun,[1] and is generally regarded to be part of an expanding solar corona.[2] Superposed on the more or less steady flow are occasional localized enhancements in density and velocity. They are often, but not always, associated with flares and other dramatic events on the surface of the sun. It is the interaction of this plasma stream, generally referred to as the "solar wind", and the geomagnetic field that leads to the formation of the current sheath required to terminate the geomagnetic field. A variety of geophysical phenomena such as magnetic storms, aurorae, and ionospheric disturbances are believed to be closely associated with this interaction.

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Although many details remain to be filled in, it is now determined that the magnetopause intersects the sun-earth line at a geocentric distance of about 10 earth radii, that this distance may vary by a few earth radii depending on the intensity of the solar wind, and that the geomagnetic field extends to much greater distances on the night side of the earth than on the day side.

The most extensive measurements of magnetic fields and energetic particles in the distant sunward portion of the magnetosphere have been those made by Explorer 12 during the period from August 16 to December 16 in 1961. A sample of data that reveals many features of the conditions near the magnetopause is shown in Figure 1.[3] These are for the inbound pass of September 13, on which occasion the satellite was almost precisely on the subsolar point at the moment of crossing the magnetopause. The authors emphasize that these data should not be regarded as average or typical, but only as an example of a wide variety of phenomena of similar and different nature observed by Explorer 12.

Data from the three magnetometers on Explorer 12 are shown on the lower part of Figure 1. Also included is a continuous line to represent the intensity $|B|$ of the theoretical geomagnetic field calculated by extrapolation of the values measured at the earth's surface under the assumption (not entirely true) that no electric currents flow overhead. The data points and broken curves represent the intensity and direction of the magnetic field actually measured in space. The angle α lies between the direction of the magnetic field and the spin axis of the spacecraft. The angle ψ lies between the plane containing the magnetic field and the spin axis and the plane containing the sun direction and the spin axis. These data show that the regular geomagnetic field characteristic of the magnetosphere was effectively terminated at about 8.2 earth radii. The boundary itself was about 200 km thick, and characterized by a change in intensity of about 100γ ($1\gamma = 10^{-5}$ gauss) and a change in the direction roughly equivalent to a reversal. Within the magnetosphere, the magnetic field was generally of a regular dipole nature, although the scalar magnitude of the field just inside the magnetopause was approximately twice the theoretically extrapolated value. Beyond the magnetopause, the magnetic field was irregular or disordered, and generally weaker than in the magnetosphere. Direct evidence is thus provided for the compression and confinement of the geomagnetic field, presumably under the impact of solar plasma as described in the pioneering theoretical studies commenced over three decades ago by Chapman and Ferraro, and reviewed recently by Chapman.[4]

Data from some of the particle detectors carried on Explorer 12 are shown in the upper part of Figure 1. These are an Anton 302 Geiger-Müller tube, the shielding of whose active volume correspond to the end-point range of electrons of energy 1.6 Mev or of protons of energy 20 Mev; and a two-channel magnetic electron spectrometer with passbands $40 \leqslant E \leqslant 50$ kev (SpL) and $80 \leqslant E \leqslant 100$ kev (SpH) and a background detector (SpB). In presenting the results from the spectrometer, the counting rates of both the low-energy and the high-energy channels were corrected for the contribution of noncollimated particles by subtracting the rates of the background detector. The results show that the net counting rates observed at distances greater than 8.2 earth radii are not discernibly different from the interplanetary values due, presumably, to galactic cosmic rays. As Explorer 12 passed the magnetopause, however, the counting rates immediately began to rise and continued to do so, though less rapidly, as the satellite penetrated a substantial distance into the magnetosphere. Direct evidence is thus provided that durable geomagnetic trapping of charged particles occurs at heights up to but not greater than that of the magnetopause.

Although the recognition and verification of an ever-present solar wind has been a development extending over little more than the last decade, the principles underlying the formation of the associated permanent magnetopause had been determined many years before, principally by Chapman and Ferraro, in connection with the transient problem in which an immense and rapidly advancing cloud or jet of solar plasma is considered to engulf the earth and produce a magnetic storm. The goal of much of the early work was to infer how the stream and the geomagnetic field would be altered by their interaction. To attain this goal, Chapman and Ferraro simplified the problem in various ways and proceeded with a discussion that was partly quantitative and partly intuitive. They dealt with solar plasma free from any magnetic fields, and regarded the earth as devoid of any atmosphere in the regions penetrated by the solar plasma. The plasma was considered to be a medium of such high electrical conductivity that its interior is permanently shielded from all external magnetic fields by electric currents induced in a thin surface layer. Interaction between the currents and the magnetic field leads to forces that retard the advance of the stream surface. Since the retardation is nonuniform, the surface would become distorted and the geomagnetic field would "carve out a hollow" in the stream. In this way, the rapid increase of the horizontal magnetic force that occurs in the initial phase of a magnetic storm is shown to be the natural consequence of the rapid approach toward the earth of a cloud of solar plasma.

Out of these and subsequent studies has emerged the formulation of a precise mathematical model that embodies in an idealized way some of the more important aspects of the interaction between a stream of solar plasma and the geomagnetic field. According to this model, the magnetic field in the hollow, or the magnetosphere in today's parlance, satisfies the equations for a static magnetic field in a vacuum, that is

$$\operatorname{div} \underset{\sim}{B} = 0 \quad , \qquad \operatorname{curl} \underset{\sim}{B} = 0 \tag{1}$$

The total magnetic field $\underset{\sim}{B}$ in the magnetosphere is the sum of the permanent magnetic field $\underset{\sim}{B}_p$ and the induced magnetic field $\underset{\sim}{B}'$ due to currents in the stream surface. The permanent magnetic field is generally approximated by a three-dimensional dipole singularity at the origin (the center of the earth), thus

$$\underset{\sim}{B}_p = - (M_p/r^3) \, (\hat{\theta} \sin \theta + \hat{r} \, 2\cos \theta) \tag{2}$$

where the coordinate system is fixed with respect to the dipole axis so that r refers to the radial distance from the origin, θ to the polar angle measured with respect to the northern extension of the dipole axis, and $\hat{\theta}$ and $\hat{r}$ are unit vectors in the direction of increasing θ and r. The magnetic moment of the dipole is given by $M_p = a_e^3 B_{p_0}$, where a_e represents the radius of the earth (6.37×10^8cm) and B_{p_0} represents the intensity of the geomagnetic field at the magnetic equator (0.312 gauss). Since the location of the boundary is unknown, it is necessary to specify two boundary conditions to determine a unique solution. One is that the normal component of the geomagnetic field must vanish at the interface with the plasma stream, that is

$$\underset{\sim}{B}_s \cdot \hat{n}_s = B_n = 0 \tag{3}$$

where $\underset{\sim}{B}_s$ refers to the value of $\underset{\sim}{B}$ at the boundary and $\hat{n}_s$ refers to the unit normal. The second is that the pressure exerted on the boundary by the particles of the solar plasma be balanced by the magnetic pressure $B_s^2/8\pi$. It is usually considered that the particles are, in effect, specularly reflected at the boundary, in which case

$$B_s^2/8\pi \;=\; 2mn \;\left[(\underset{\sim}{V} - \underset{\sim}{v}) \cdot \hat{n}_s\right]^2 \tag{4}$$

where m, n, and $\underset{\sim}{V}$ refer to the mass, number density, and velocity of the ions (generally considered to be protons) of the undisturbed incident stream, and $\underset{\sim}{v}$ refers to the local velocity of the surface.

This problem has not been solved exactly, although Chapman and Ferraro have solved a number of related problems intended to illuminate properties of the anticipated results. Use was often made in these analyses of the approximation that the intensity of the magnetic field at the boundary is given by some multiple of the tangential component B_t of the geomagnetic dipole field, that is by

$$B_s = 2fB_t \quad (5)$$

where f is a constant.

Mrs. Audrey L. Summers and the author have recently applied this approximation to the actual transient Chapman-Ferraro problem and calculated the deformation of an initially flat-faced plasma cloud as it sweeps past the earth. The results for the equatorial plane are shown in Figure 2 for the special case in which the plasma cloud has a density of 2.5 protons/cm.^{3}, is advancing toward the earth with a velocity of 500km./sec., and f is equated to unity. The front face of the plasma cloud is considered to be a plane surface at right angles to the direction of advance when at a geocentric distance of 20 earth radii. Successive positions of the front of the advancing plasma cloud are as shown. This figure, which is merely the quantitative counterpart of sketches made long ago on a more qualitative basis by Chapman and Ferraro, illustrates how the magnetic field shields a large region surrounding the earth from the solar plasma. It also illustrates how the hollow approaches its final steady-state form, everywhere except far downstream from the earth, within a few minutes of the arrival of such a plasma cloud.

With the growing realization of the existence of a permanent solar wind, attention has turned in recent years to the steady-state Chapman-Ferraro problem in which the geomagnetic dipole field is embedded in a steady flow of infinite extent. The mathematical formulation of the problem is identical to that described by equations (1) through (4) except that the boundary is assumed fixed in space ($\underset{\sim}{v} = 0$)[5]. This problem has been studied extensively by several investigators and results obtained using several different approaches are now in substantial agreement.[6,7]

The calculated form of the hollow in a steady solar wind blowing at right angles to the dipole axis is as shown in Figure 3.[8] For simplicity, the coordinates of the hollow are illustrated for only one quadrant. Those for the other quadrants follow immediately by symmetry. The cavity is found to be round near the nose, to flare out monotonically with increasing distance downstream, and to approach a finite lateral width at great distances. Except for failure of the cavity to close far downstream of the earth, the result is thought to be in general conformity with the actual shape of the magnetosphere. Lack of closure in the calculated shape is the immediate consequence of the assumption that the particles are considered to travel in straight lines without any interaction whatsoever until they encounter the thin current sheath comprising the boundary. The shape of the tail is, however, very sensitive to small alterations in the basic assumptions of the theory. It has been shown, for instance,[9,10,11] that even a very small pressure applied uniformly over the exterior of the boundary results in a profound shortening of the tail. On the other hand, other considerations suggest that the stream is not capable of curving sufficiently rapidly to follow the contour indicated by these results. Resolution of this apparent inconsistency may reside in the possibility that the downstream portion of the boundary of the geomagnetic field does not necessarily coincide with the boundary of the streaming solar plasma. It appears quite plausible, in fact, that the latter may trail off from the vicinity of the widest portion of the cavity and enclose a dead-water region of nearly uniform pressure much as in the more familiar case of separated free-streamline flow of a nonconducting fluid.[9]

It is thus not surprising that discrepancies have been noted between the calculated and observed shape of the night side of the magnetosphere. Direct observations in this region are confined, however, to the single case of Explorer 10 which measured the magnetic field and plasma flux over geocentric distances of 1.8 to 42.6 earth radii during the period March 25-27, 1961.[12,13] It is found that the close-in data are generally consistent with the theoretical field calculated by extrapolation of surface values. Farther out at distances between about 8 and 22 earth radii, the field was directed away from the sun and earth, although presumably still confined within the magnetosphere boundary since plasma fluxes were not detected. At distances greater than 22, but less than 32 earth radii when a geomagnetic storm commenced suddenly, Explorer 10 evidently crossed the boundary on six principal occasions. In this range, plasma having a density of the order of 10 protons/cm.[3] and a velocity of about 500 km./sec. was observed most of the time. On several occasions, however, it disappeared for a period of several minutes to about an hour, and then reappeared. The immediate interpretation that the satellite finds itself alternately in and out of a fast moving plasma stream is supported by remarkable and coincident changes in the magnetic field. Whenever the plasma disappeared, the magnetic field tended to become radial from the earth and its strength decreased smoothly with increasing distance from the earth. When the plasma reappeared, the field became irregular, and its mean direction shifted by about 90°. The experimenters have interpreted the results as indicating that the tail of the geomagnetic cavity in a steady solar wind is actually much broader than calculations based on the Chapman-Ferraro model would indicate. An alternative explanation has recently been proposed, however, in which the appearance and disappearance of plasma-free regions are attributed to expansions and contractions of the magnetosphere in response to changes in intensity of the plasma stream.[14] A rather particular series of changes in intensity is required to account for the observations of Explorer 10, but evidence from surface magnetograms and from the measured plasma intensities is introduced to show that such events may well have taken place. In conclusion, it may be fairly stated that conditions in the distant downstream portion of the magnetosphere are far from fully described, let alone, comprehended, at the present time.

The underlying cause of the pronounced dent in the high latitude daytime side of the boundary can be seen upon examination of the magnetic field lines illustrated in the left part of Figure 4.[8] These results are drawn for a solar wind having a density n of 2.5 protons/cm.^{3} and a velocity V of 500 km./sec., but can be altered easily for other conditions, since all dimensions scale in proportion to $(nV^2)^{-1/6}$. An important point is that there is but one field line in each hemisphere that extends from the earth to the magnetosphere boundary. At the neutral points where these field lines meet the boundary the magnetic field must vanish much as the velocity of an incompressible flow must vanish at a stagnation point. Since equation (4) indicates that $\underset{\sim}{V}\cdot\hat{n}_s$ must vanish where B_s vanishes in the steady-state Chapman-Ferraro theory, it follows that the magnetosphere boundary is parallel to the direction of the incident stream at the neutral points. That the boundary shown in Figures 3 and 4 does not satisfy this condition perfectly is a result of the use of the approximation given by equation (5). Numerical results obtained recently[6,7] without recourse to this approximation are more satisfactory in this particular, and the indentation is slightly deeper in the vicinity of the neutral points than illustrated in Figures 3 and 4. The neutral points themselves are of particular physical significance because all field lines that comprise the boundary diverge from one neutral point and converge to the other, and also because charged particles from the region occupied by solar plasma may travel down the lines of force from the neutral point to the earth.

The dipole axis is not always at right angle to the direction of the incident solar wind. Indeed, if the wind is considered to travel exactly radially outward from the sun, as in fact it seems very nearly to do, the inclination of the solar wind direction as viewed in geomagnetic coordinates varies through an angle range of $\pm 34.5^{\circ}$ in the course of the year. As a result, calculations similar to those described above using the approximation of equation (5) have been carried through for several orientations of the solar wind relative to the dipole axis.[15,16,17,11] (No comparable results obtained without recourse to this approximation have yet been reported.) The results for the case in which the solar wind is at maximum obliquity is shown in the right half of Figure 4. The principal effect is a general rotation of the magnetosphere boundary, as viewed in geomagnetic coordinates, so that the great open tail continues to trail off in the downstream direction. The positions of the neutral points move somewhat, as viewed in the same coordinate system, but the change in latitude of these points is much less than the angular change of the stream direction. The degree of exposure to the solar stream of the critical regions around the neutral points through which charged particles may penetrate becomes very asymmetric, however, with the summer polar region appearing to be much more susceptible to such entry than the winter polar region.

Ground-based observational evidence that such phenomena may actually occur is provided by magnetometer records from the polar regions. Fukushima has assembled a considerable body of data gathered during the IGY (July 1957 - December 1958) and the Second Polar Year (August 1932 - August 1933), and analyzed it in various ways according to the time of day and year, and the degree of disturbance of the world-wide geomagnetic field.[18] The results show that the polar regions are constantly disturbed, even at periods when the planetary geomagnetic field is very quiet. Two of the many summary plots presented by Fukushima are reproduced in Figure 5. These show the latitudinal distribution of the average geomagnetic disturbance near the noon and midnight meridians for the case of $K_p = 0_o$, that is for the very quietest times as indicated by the planetary geomagnetic index, at two selected sets of times extending over the entire period of the IGY. The results show that the magnitude of the polar-cap disturbance is of the order of a few or several tens of gammas, that both polar caps are equally disturbed when the sun-earth line is perpendicular to the geomagnetic dipole axis, and that the disturbances are a maximum at summer noon, and a minimum at winter midnight. These results appear to be consistent with what might be anticipated on the basis of direct invasion of charged particles or propagation of hydromagnetic waves into the polar regions along the field lines from the neutral points on the magnetosphere boundary.

Although there is remarkably good general correspondence between the results of the highly idealized Chapman-Ferraro theory and those measured in space, it would be an exaggeration to claim that all, or even most, of the important features are described adequately for all purposes. Already noted is the inadequacy of the theory for the distant night side of the magnetosphere. The results shown in Figure 1 display, in addition, the existence near the subsolar point of a region of irregular field beyond the magnetosphere boundary that is unanticipated on the basis of the classical theory. A growing body of evidence is now accumulating that suggests that the region of irregular fields is associated with the existence of a general interplanetary magnetic field. The nature of the interaction can not be simple, however, since both space experiments and ground-based evidence indicate that the intensity of this field is of the order of only a few gamma during quiet times, and is therefore much smaller and less irregular than, for instance, the field indicated in Figure 1 beyond 8.2 earth radii.

It is improbable that the interplanetary magnetic field is sufficiently strong to have direct dynamic effects, since the energy density $B^2/8\pi$ of the field is generally much smaller than the kinetic energy density $nmV^2/2$ of the stream. For example, if $B = 5\gamma$, $n = 10$ protons/cm.^{3}, and $V = 300$km./sec., the ratio $4\pi nmV^2/B^2$, which is also identified as the square of the Alfvén Mach number M_A, is equal to about 76. Axford[19] has recently pointed out, however, that the interplanetary magnetic field has the important effect of causing the solar wind to behave as a continuous fluid over length scales that are large compared with the proton Larmor radius, i.e. the radius of curvature of the path of a proton in a uniform magnetic field. The intensity of the magnetic field required to accomplish this effect, moreover, is not large, since the Larmor radius is about 600 km. for a 300km./sec. proton in a magnetic field of 5γ, whereas a typical dimension of the magnetosphere is of the order of 10^5km. It is therefore necessary, according to this view, to consider the solar plasma as a continuous rather than a "free-molecule" flow in its interaction with the magnetosphere. Since further examination shows that the Alfvén Mach number is greater than unity, a shock wave in the form of a detached bow wave must be produced upstream of the magnetosphere. This is not an ordinary gasdynamic shock wave, however, but is of the collision-free type relying on nonlinear interactions of magnetohydrodynamic waves to produce the required randomization of particle motions. Since the scale of the field and plasma irregularities is thus linked to the Larmor radius of the particles, and is hence large compared with the dimensions of the satellite, the region downstream of the shock wave would appear to be highly irregular, as had already been observed at that time during the flights of Pioneers 1, 4, and 5.

Although the concepts described above must still be considered somewhat tentative, results, such as those shown in Figure 6, of further theoretical studies on the shape and location of the shock wave and on the conditions existing in the transition region between it and the magnetosphere appear to support the general interpretation.[20] Of particular significance is the result that the geocentric distances along the sun-earth line to the boundary of the magnetosphere and to the shock wave are about 10 and 14 earth radii. These numbers are shown[20] to be in substantial agreement with those observed by Pioneers 1, 4, and 5, provided that the region of fluctuating magnetic field and counting rate of energetic particles is interpreted as representing the transition region between the shock wave and the magnetosphere. This interpretation is suggested by the calculated results displayed in the small inserts of Figure 6 for the detailed structure of the transition region between a steady transverse magnetic field (the magnetosphere) and an adjacent plasma (the solar wind) containing a smaller magnetic field. Four inserts are presented because the original analysis[21,22] discloses the results depend critically on whether the two magnetic fields are parallel or anti-parallel, and on whether the Alfvén Mach number M_A is greater or less than 2. If M_A' based on the velocity component normal to the shock wave is less than 2, as occurs well back along the shock wave in general, and near the nose if the interplanetary magnetic field is sufficiently strong, the calculated magnetic field profiles in the transition region are oscillatory and orderly. If M_A is greater than 2, as may occur over much of the nose of the geophysical shock wave if the transverse component of the interplanetary magnetic field is not too large, the magnetic field in the transition region is very irregular, although still oriented in the same direction as the interplanetary field.

Comparison of Figures 1 and 6 shows that the magnetic field measured in space on the inbound pass on September 13 bears a close resemblance to the calculated results for antiparallel fields with M_A greater than 2, although results observed on some other occasions have been shown to bear a closer resemblance to the results for M_A less than 2.[20] It may be observed, however, that the geocentric distance to the boundary of the magnetosphere shown in Figure 1 is somewhat less than in the example presented in Figure 6. This can be accounted for by asserting the density and/or velocity of the solar wind was greater at this time than the values used to make Figure 6. This assertion is supported by the fact that the geomagnetic field observed at this time on the earth's surface was moderately disturbed, and by the fact that the experimenters report[23] that the magnetosphere boundary was unusually close to the earth on this occasion.

In summary, considerable progress has been made in recent years in understanding the nature of the distant geomagnetic field and its interaction with the solar wind. Observational data obtained with space experiments have substantially verified the broad description of the principal features of this interaction provided by the classical theory of Chapman and Ferraro. Recent theoretical studies have contributed to the more detailed comparisons by providing increasingly complete knowledge of the solutions implicit in the statement of the basic theory. Much work remains to be done, however, in identifying and developing an understanding of the underlying causes for several phenomena observed in the data, but not presently accounted for by theory. It is anticipated that the heavy concentration of effort now going into these problems will yield such a better understanding during the course of the next few years. It is to be hoped that with it will come an improved appreciation for the varied and subtle links connecting natural phenomena on the sun and earth.

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Figure Titles

1. Particle and magnetic field measurements with Explorer 12. (From Freeman, Van Allen, and Cahill, J. Geophys. Res., 1963.)

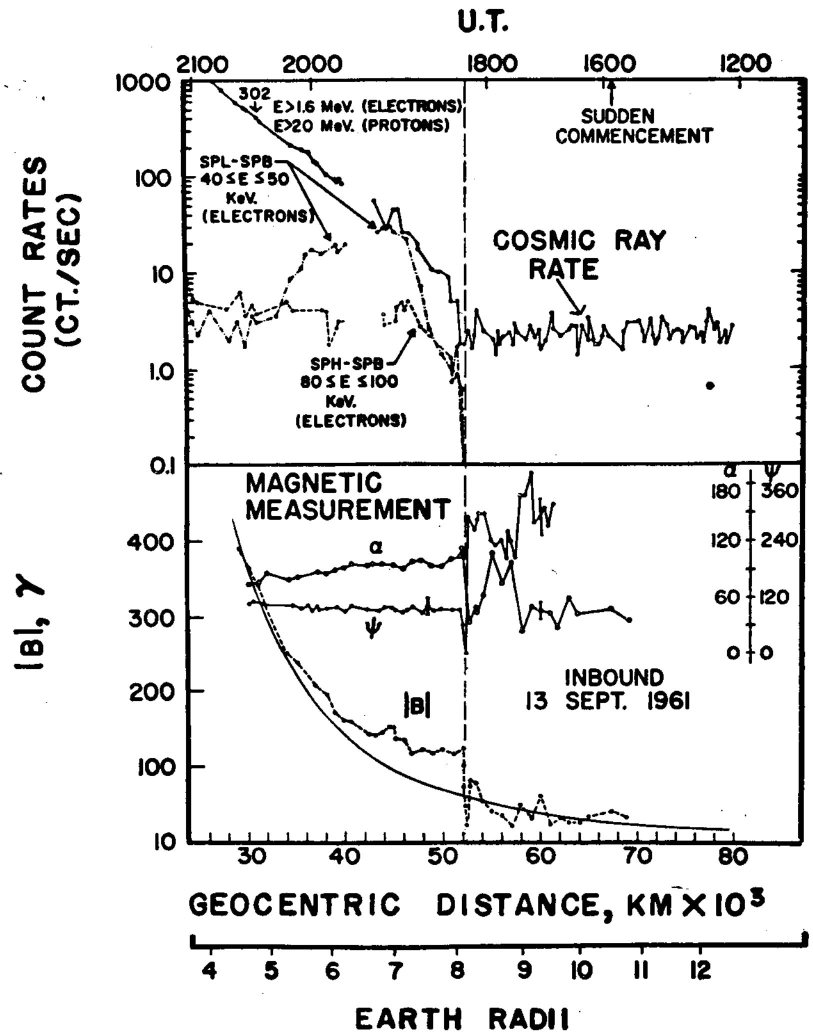
2. Successive positions in the equatorial plane of the front of a plasma cloud advancing toward the earth with V = 500km./sec. and n = 2.5 protons/cm.^{3}

3. Form of the boundary of the geomagnetic field in a steady solar wind, as indicated by approximate solution of the Chapman-Ferraro problem.

4. Traces of the boundary of the geomagnetic field in the meridian plane containing the dipole axis and the velocity vector of the incident solar wind for steady flow at 0^o or 34.5^o inclination to the geomagnetic equatorial plane, V = 500km./sec., n = 2.5 protons/cm.^{3}

5. Polar magnetic disturbance near the noon and midnight meridians at times during the IGY when $K_p = 0_o$ and the sun-earth line is inclined at 0^o or 34.5^o to the geomagnetic equatorial plane. (From Fukushima, Report of Ionosphere and Space Research in Japan, 1962.)

6. Traces of the magnetosphere boundary and shock wave for a steady solar wind with V = 600km./sec., n = 2.5 protons/cm.^{3}, and B = 5 γ. (From Spreiter and Jones, J. Geophys. Res., 1963)



U.T.
2100
2000
1800
1600
1200
1000
100
10
1.0
0.1
COUNT RATES
(CT./SEC)
302
E>1.6 MeV. (ELECTRONS)
E>20 MeV. (PROTONS)
SPL-SPB
40 ≤ E ≤ 50
KeV.
(ELECTRONS)
SPH-SPB
80 ≤ E ≤ 100
KeV.
(ELECTRONS)
SUDDEN
COMMENCEMENT
COSMIC RAY
RATE
MAGNETIC
MEASUREMENT
α
ψ
|B|
INBOUND
13 SEPT. 1961
|B|, γ
400
300
200
100
10
180
360
120
240
60
120
0
0
30
40
50
60
70
80
GEOCENTRIC DISTANCE, KM X 10³
4
5
6
7
8
9
10
11
12
EARTH RADII

Figure 1.

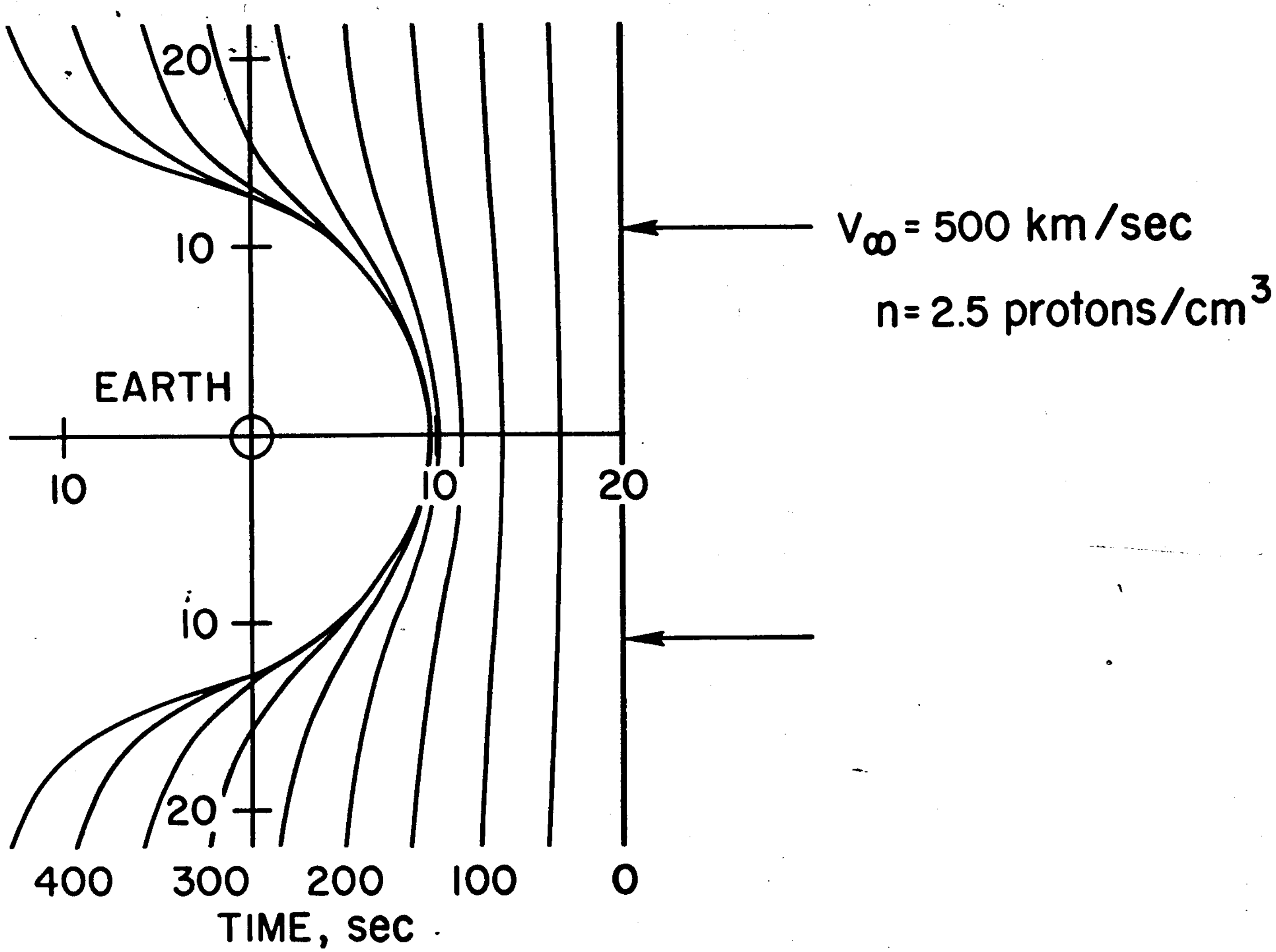


Figure 2.

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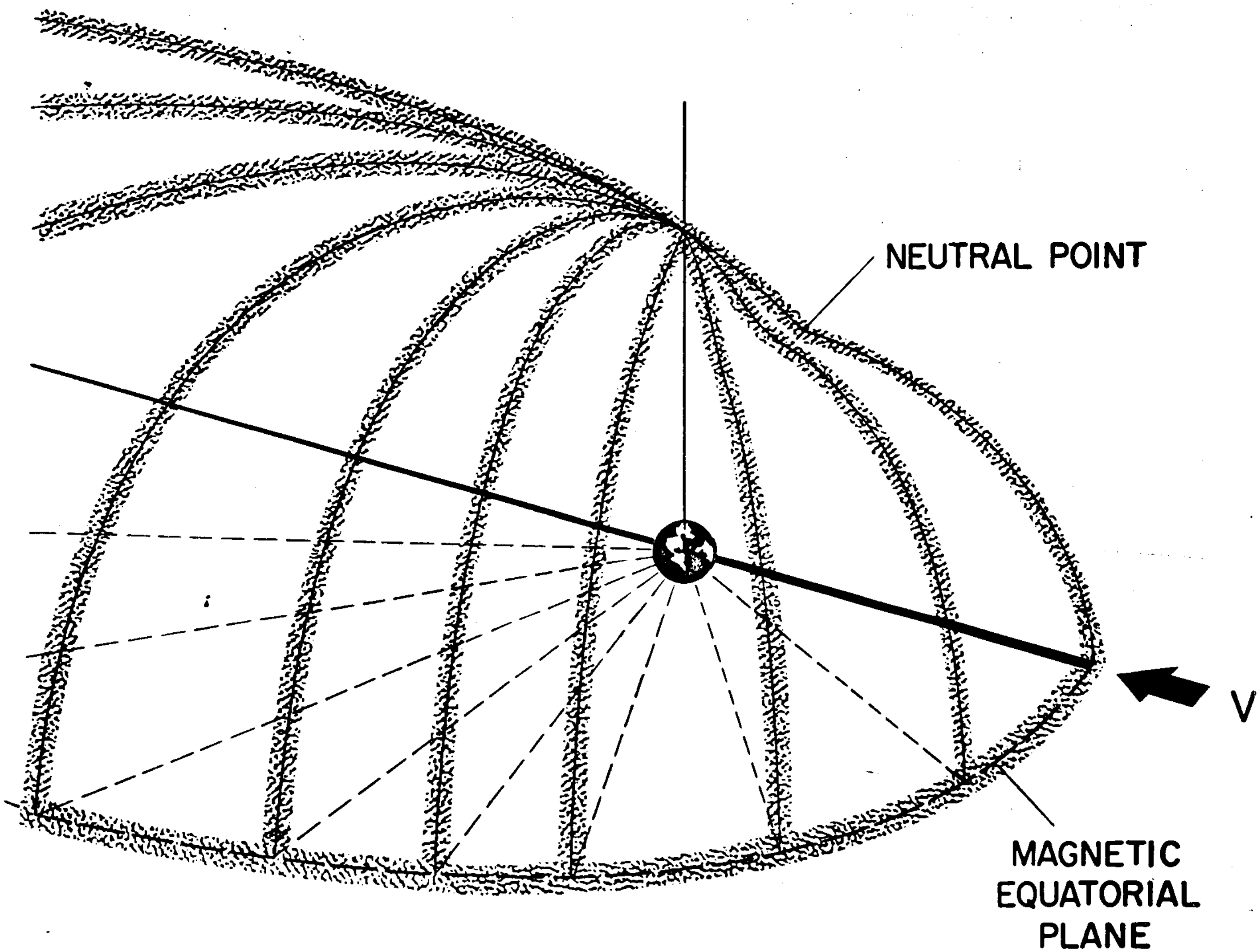

Figure 3.

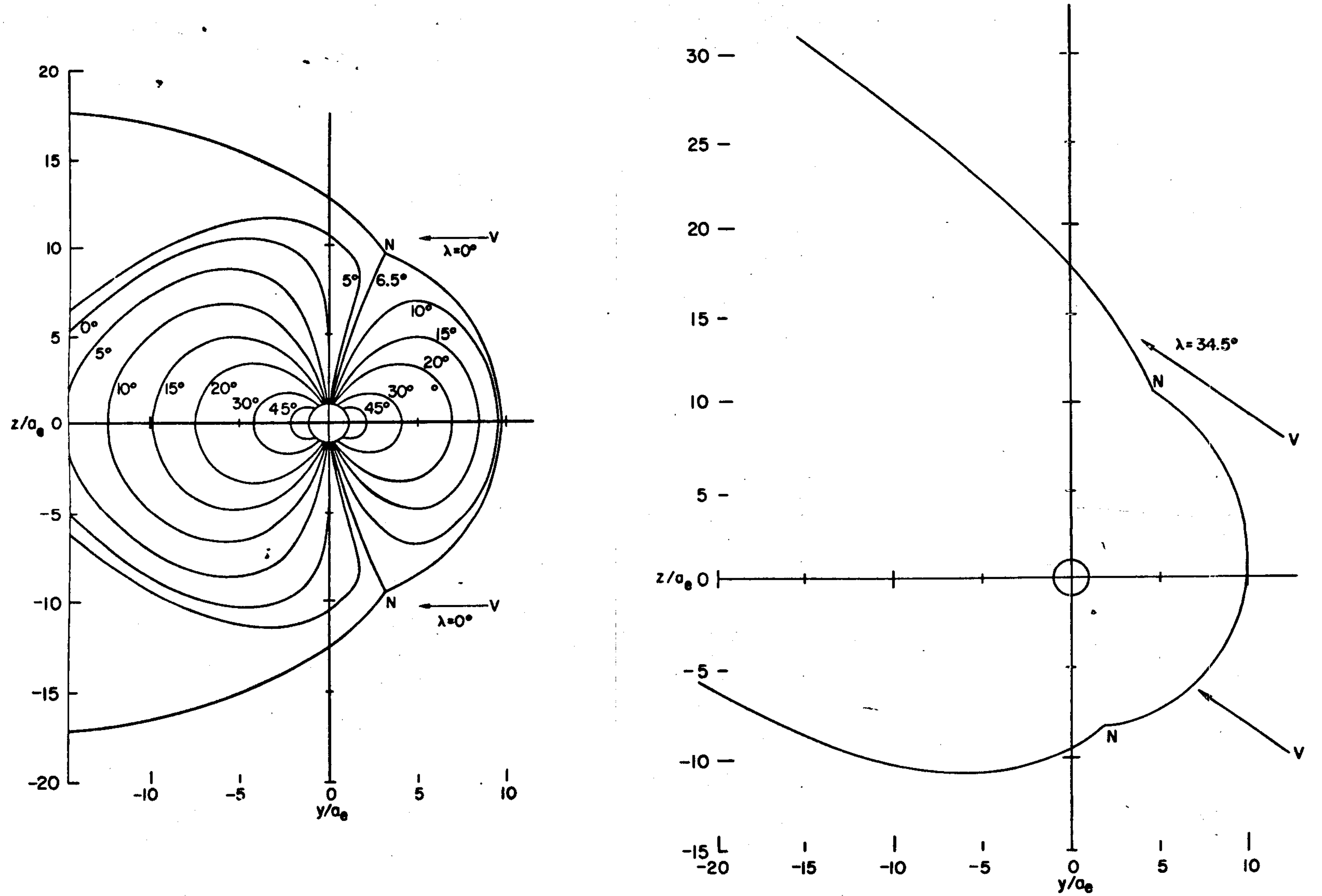

Figure 4.

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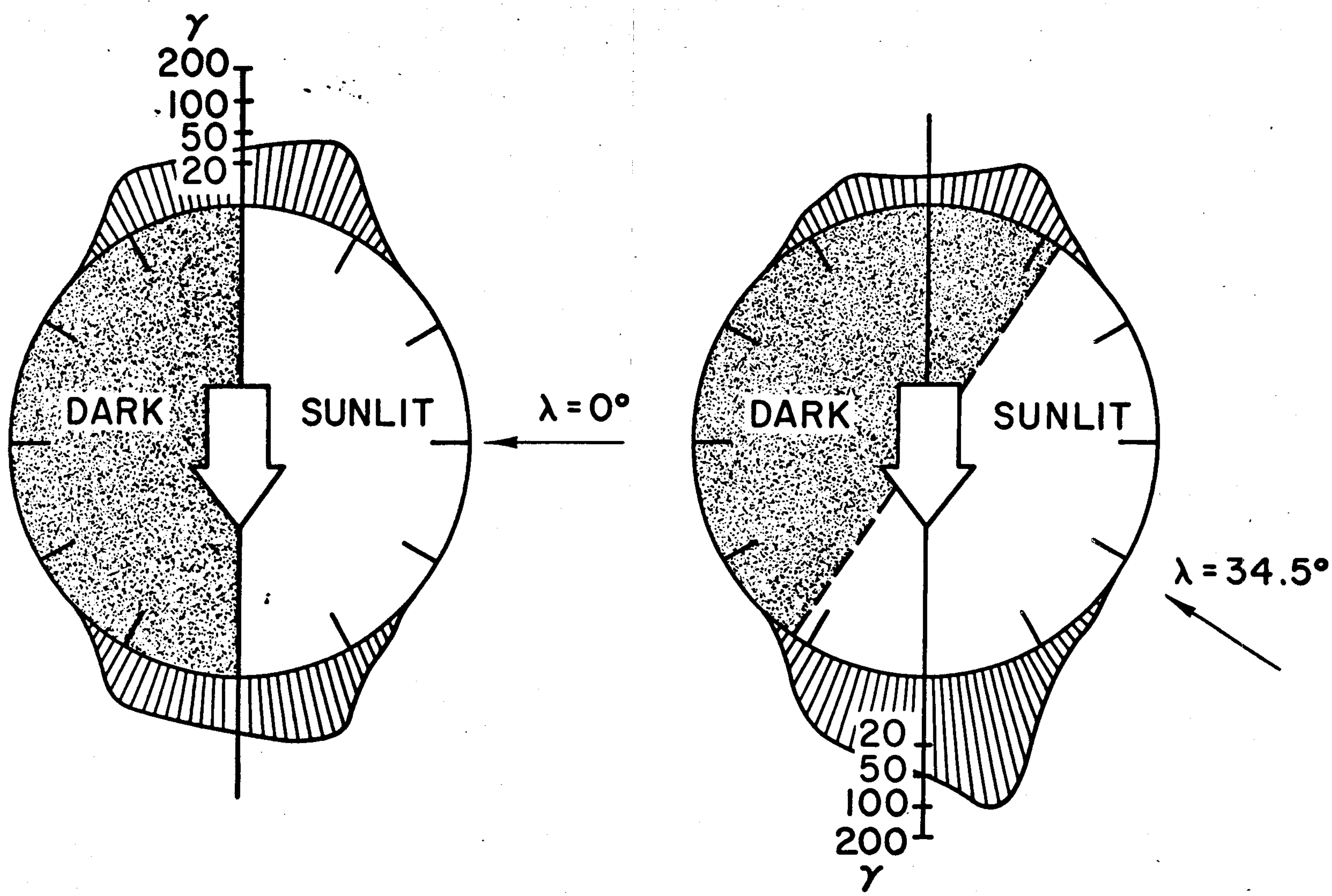
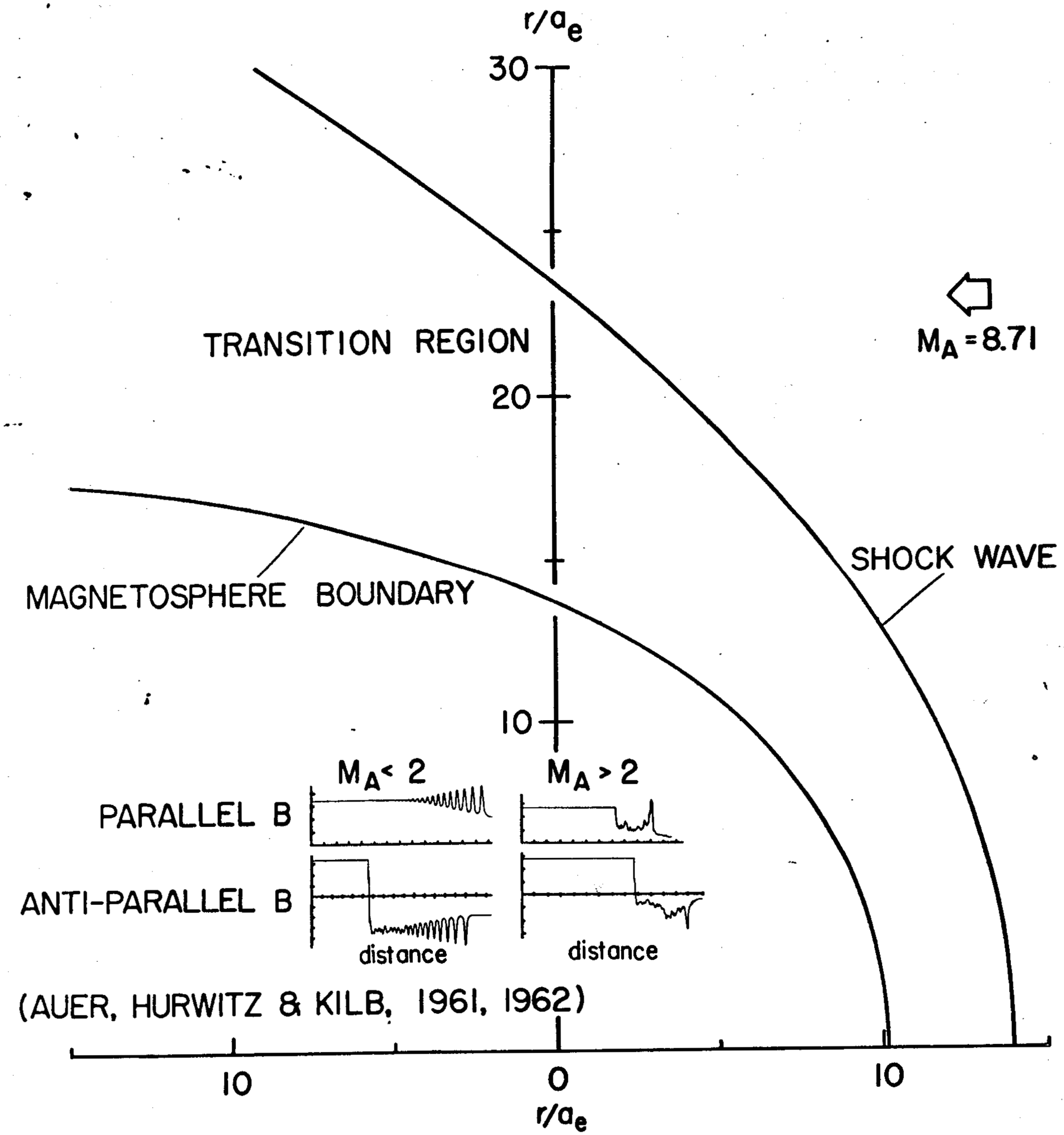


Figure 5.

A-30691-8



r/ae
30
20
10
TRANSITION REGION
MAGNETOSPHERE BOUNDARY
SHOCK WAVE
MA = 8.71
MA < 2
MA > 2
PARALLEL B
ANTI-PARALLEL B
distance
distance
(AUER, HURWITZ & KILB, 1961, 1962)
10
0
10
r/ae

Figure 6.